Parallel Unsteady Turbopump Flow Simulations For Reusable Launch Vehichles

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- INTRODUCTION
  - Major Drivers of the Current Work
  - Objectives
- APPROACH / PROGRESS
  - Computational models
  - Code parallelization
  - Time-accuracy and integration schemes
- SUMMARY

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Major Drivers of the Current Work

- TOOLS FOR AEROSPACE DESIGN

  Decrease design cycle time ⇒ Rapid turn-around

  Increase design/process fidelity ⇒ High accuracy and low variation

  Increase discipline integration ⇒ Increased range of options via IT

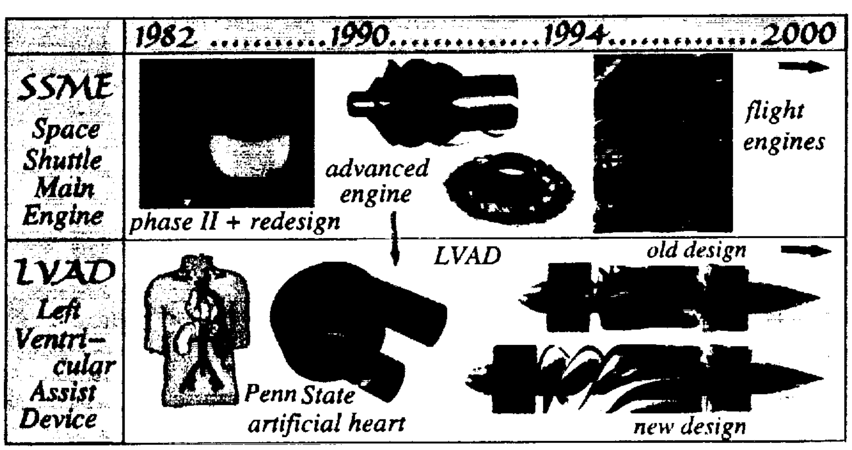
Turbo-pump component analysis ==> Entire turbo pump simulation

- HPCC CAS Level I milestone :

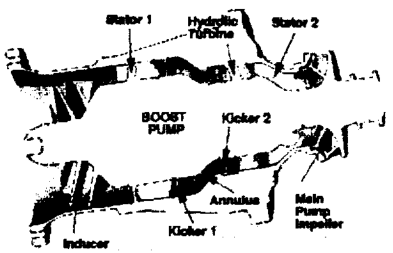
To demonstrate a 1000 times speed up in June 2001 over what was possible in FY92.

Objectives

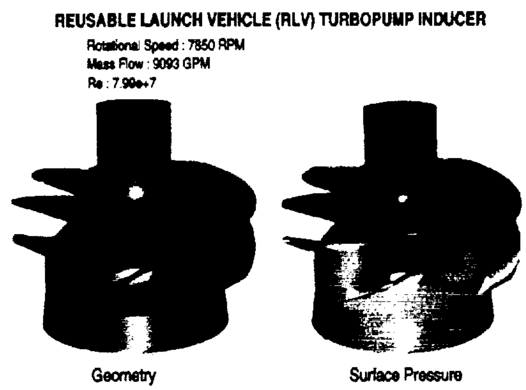
- To enhance incompressible flow simulation capability for developing aerospace vehicle components, especially, unsteady flow phenomena associated with high speed turbo pump



Computational Model
RSTS BOOST PUMP



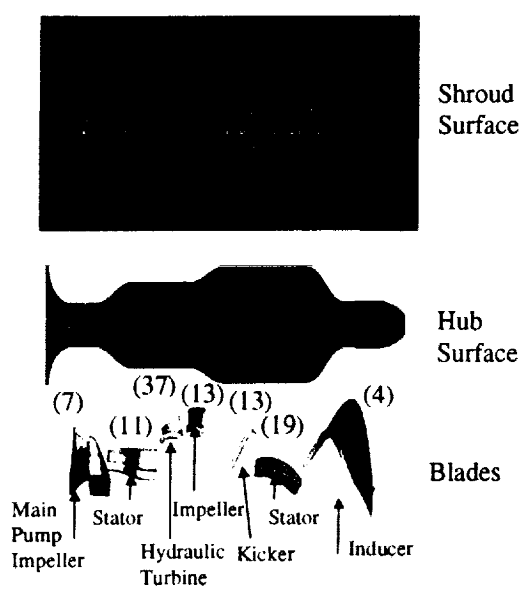
1- Inducer (R)
2- Stator 1 (S)
3- Inducer Kicker (R)
4- Annulus (S)
5- Kicker (R)
6- Hydrolic Turbine (R)
7- Stator 2 (S)

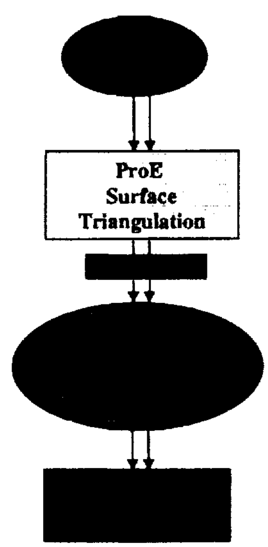


COMPUTATIONAL CHALLENGES :

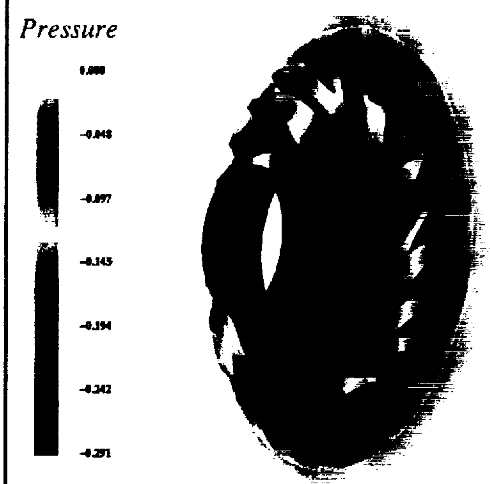
- **Cost due to time-accurate incompressible flows**
- **Moving grid system**
- **Code parallelization**

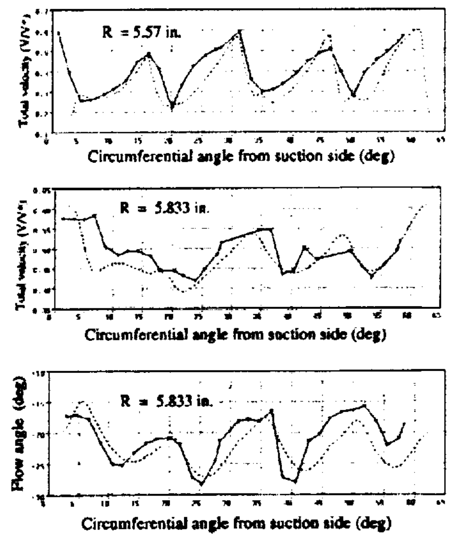
Boost Pump Computational Model



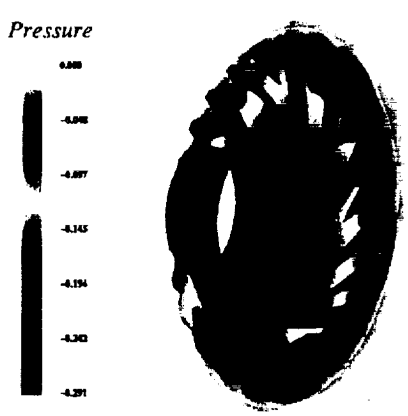


SSME Impeller

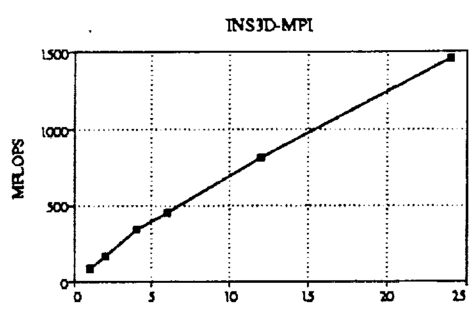




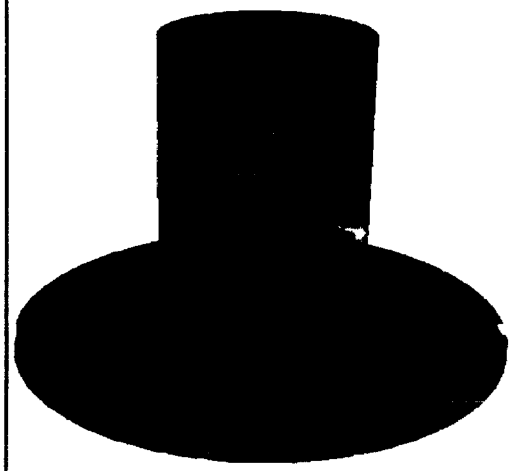
INS3D Parallelization



INS3D-MPI - coarse grain
First release
T. Faulkner & J. Dacles
MPI coarse grain + OpenMP
Debugging stage
H. Jin & C. Kiris
MLP (Implementation is currently underway)



Shuttle Upgrade SSME-rig1
(code validation)



[redacted]

Inlet Guide Vane (IGV)
- **15 Blades**
- **Pitch, p = 24 degrees**
- **Blade Inlet Angle (mean), $\beta_{IGV,1}$ = 90 degrees**
- **Blade Exit Angle (mean), $\beta_{IGV,2}$ = 45 degrees**

Clearance between IGV and Impeller, x = 0.12 inches

Impeller
- **6+6+12 Unshrouded Design**
- **Pitch, p = 60 degrees**
- **Blade Inlet Angle (mean), $\beta_{imp,1}$ = 23 degrees**
- **Blade Exit Angle (mean), $\beta_{imp,2}$ = 65 degrees**
- **Clearance between blade LE and Shroud, r = 0.0056 inches**
- **Clearance between blade TE and Shroud, x = 0.0912 inches**

Clearance between Impeller and Diffuser, r = 0.050 inches

Diffuser
- **23 Blades**
- **Pitch, p = 15.652 degrees**
- **Blade Inlet Angle (mean), $\beta_{dif,1}$ = 12 degrees**
- **Blade Exit Angle (mean), $\beta_{dif,2}$ = 43 degrees**

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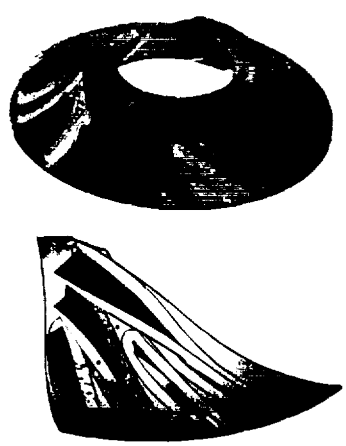
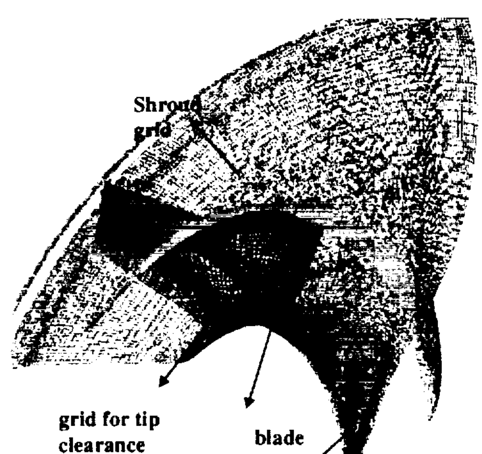
Shuttle Upgrade SSME-rig1





Unshrouded Impeller Grid :

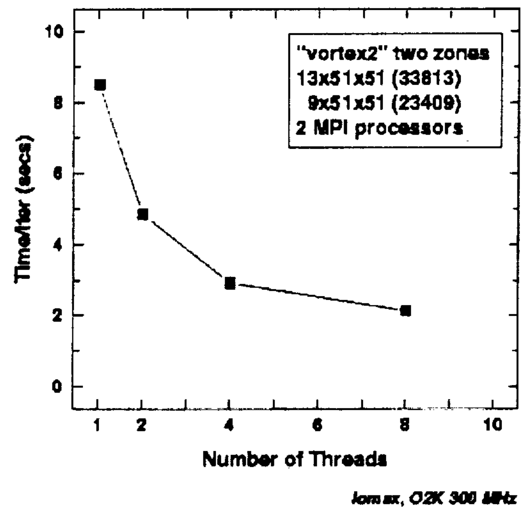
6 long blades / 6 medium blades /12 short blades
60 Zones / 19 Million Grid Points
Smallest zone : 74,025 /Largest zone : 899,248

Overset connectivity is obtained by using DCF module OVERFLOW-D

INS3D Parallelization

MPI coarse grain + OpenMP fine grain

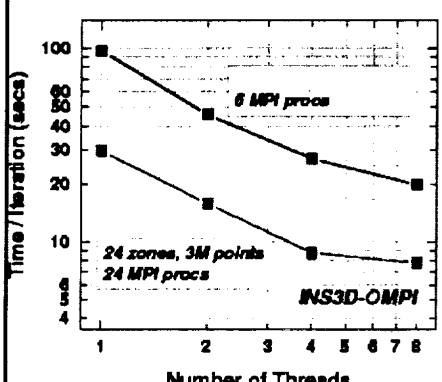
TEST CASE : 2 Zones Vortex

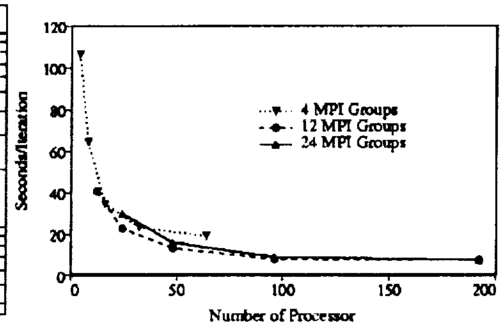


INS3D Parallelization

MPI coarse grain + OpenMP fine grain

TEST CASE : SSME Impeller





No. of processors = No. of MPI * No. of threads

Time-Accurate Formulation

- Time-integration scheme

  Artificial Compressibility Formulation

  - Introduce a pseudo-time level and artificial compressibility
  - Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

  Pressure Projection Method

  - Solve auxiliary velocity field first, then enforce incompressibility condition by solving a Poisson equation for pressure.

Pressure Projection Method

- Evaluate time-accurate features of two primitive variable methods designed for 3-D applications

  - Solve for the auxilary velocity field, using implicit predictor step

$$\frac{1}{\Delta t}(u_i^* - u_i^n) = -\nabla p^n + h(u_i^*)$$

- The velocity field at time level (n+1) is obtained by using a correction step,

$$\frac{2}{\Delta t}(u_i^{n+1} - u_i^*) = -\nabla p^{n+1} + h(u_i^{n+1}) - \nabla p^* + h(u^*)$$

- The incompressibility condition is enforced by using a Poisson equation for pressure ($p^* = p^{n+1} - p^n$)

$$\nabla^2 p^* = \frac{2}{\Delta t}\nabla \mathbf{u}^*$$

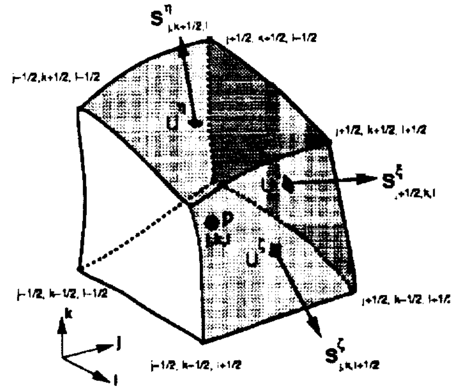
Pressure Projection Method(INS3D-FS)

- The discretization of the mass conservation equation in finite volume formulations

$$(S^{\xi}\mathbf{u})_{j+1/2}-(S^{\xi}\mathbf{u})_{j-1/2}+(S^{\eta}\mathbf{u})_{k+1/2}-(S^{\eta}\mathbf{u})_{k-1/2}+(S^{\zeta}\mathbf{u})_{l+1/2}-(S^{\zeta}\mathbf{u})_{l-1/2}=0$$

- New dependent variables,

$$U^{\xi}=\mathbf{S}^{\xi}.\mathbf{u}$$
$$U^{\eta}=\mathbf{S}^{\eta}.\mathbf{u}$$
$$U^{\zeta}=\mathbf{S}^{\zeta}.\mathbf{u}$$



- Computing time :
  80 μ-secs/grid point/iteration
- Memory usage:
  70 times number of grid points in words

Artificial Compressibility Method (INS3D-UP)

Time-Accurate Formulation

- Discretize the time term in momentum equations using second-order three-point backward-difference formula

$$\left(\frac{\partial U}{\partial \xi}+\frac{\partial V}{\partial \eta}+\frac{\partial W}{\partial \zeta}\right)^{n+1}=0 \qquad \frac{3q^{n+1}-4q^{n}+q^{n-1}}{2\Delta t}=-r^{n+1}$$

- Introduce a pseudo-time level and artificial compressibility,
- Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

$$\frac{1}{\Delta\tau}(p^{n+1,m+1}-p^{n+1,m})=-\beta\nabla q^{n+1,m+1}$$

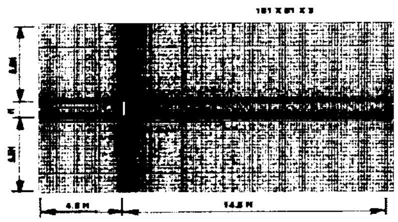
$$\frac{1.5}{\Delta t}\left(q^{n+1,m+1}-q^{n+1,m}\right)=-r^{n+1,m+1}-\frac{3q^{n+1,m}-4q^{n}+q^{n-1}}{2\Delta t}$$

- Computing time : 50-120 μ-secs/grid point/iteration
- Memory usage: **Line-relaxation** 45 times number of grid point in words
  GMRES-ILU(0) 220 times number of grid point in words

Impulsively Started Flat Plate at 90°

- GRID

  Thickness of plate = 0.3H



T=1.2

T=2.0

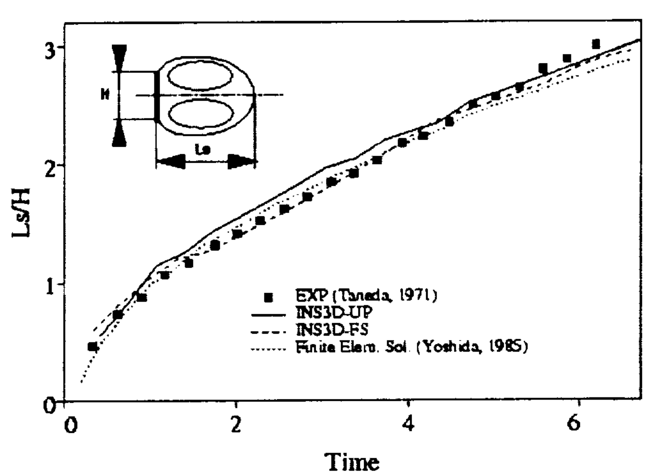
- VELOCITY MAGNITUDE

T=0.4

T=4.0

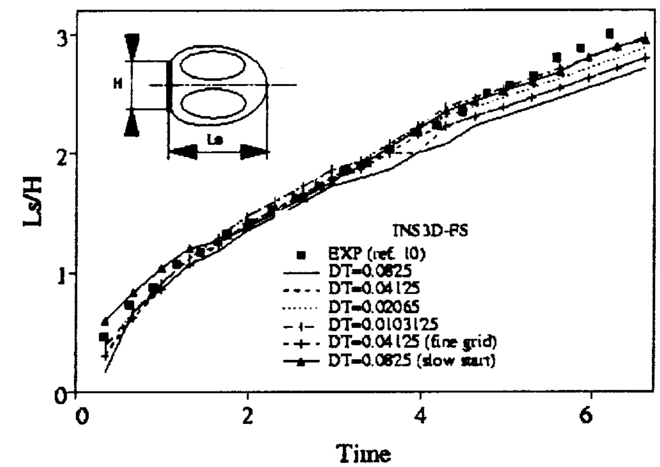
Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point



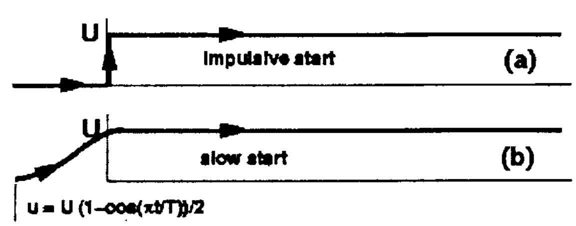
Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point
  Pressure Projection Method (INS3D-FS)



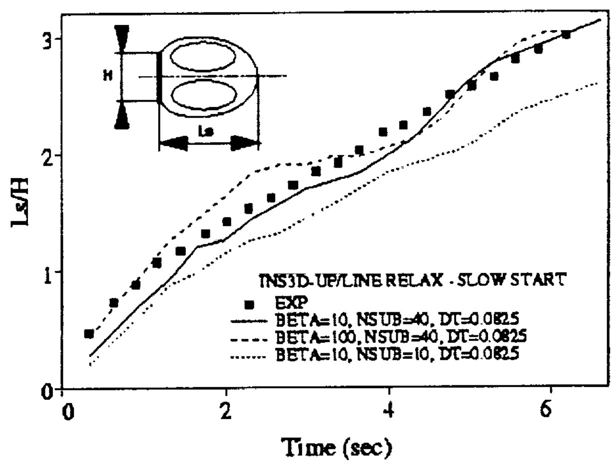
Impulsively Started Flat Plate at 90°

- Starting procedure



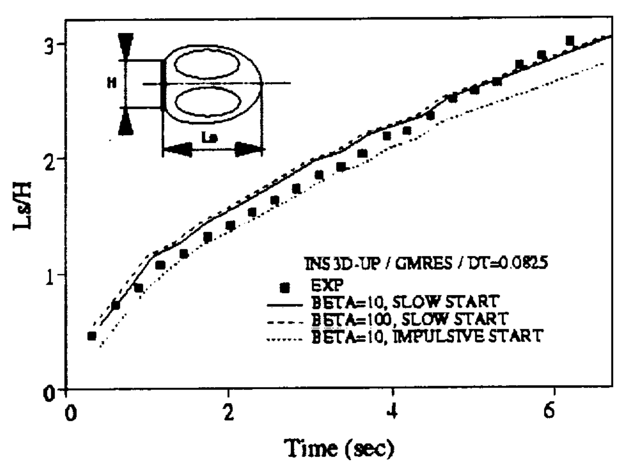
Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point
  Artificial compressibility (INS3D-UP) : Line Relaxation



Impulsively Started Flat Plate at 90°

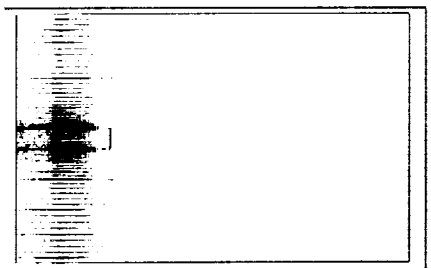
- Time History of Stagnation Point
  Artificial compressibility (INS3D-UP) : GMRES



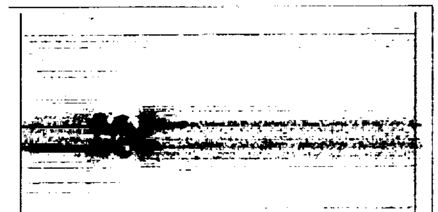
Impulsively Started Flat Plate at 90°

- VELOCITY VECTORS T=0.33

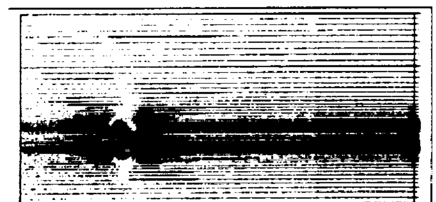
Flow is at rest and
U=1 imposed at inflow at T=0.0



INS3D-UP line-relaxation
10 subiteration at each time-step



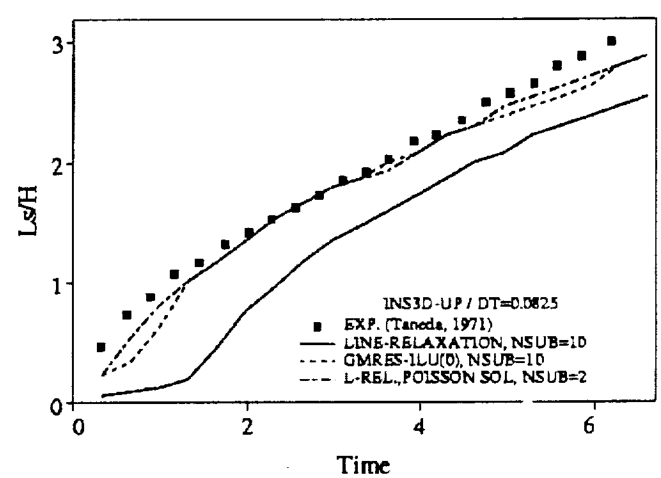
INS3D-UP / GMRES-ILU
10 subiteration at each time-step



INS3D-UP / line-relaxation
Poisson solver is incorparated
2 subiteration at each time-step

Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point
  Artificial compressibility incorporated with Poisson solver



Summary

- An efficient solution procedure for time-accurate solutions of Incompressible Navier-Stokes equation is obtained.
  - Artificial compressibility method requires a fast convergence scheme..
  - Pressure projection method is efficient when small time-step is required.
  - The number of sub-iteration is reduced significantly when Poisson solver is employed with the continuity equation.
  - Both computing time and memory usage are reduced (at least 3 times).
  - DCF module in OVERFLOW-D is incorporated with INS3D.
  - MPI /Open MP hybrid parallel code has been completed and benchmarked.
- Work currently underway
  - Multi Level Parallelism (MLP) of INS3D.
  - Overset connectivity for the validation case (SSME-rig1)
  - Experimental measurements at NASA-MSFC.
  - Computational model for boost pump